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TITLE: OPTIMAL MEASUREMENT UNCERTAINTIES FOR MATERIALS ACCOUNTING IN A FAST BREEDER REACTOR SPENT-FUEL REPROCESSING PLANT

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OPTIMAL MEASUREMENT UNCERTAINTIES FOR MATERIALS ACCOUNTING IN A FAST BREEDER REACTOR SPENT-FUEL REPROCESSING PLANT

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ABSTRACT

Optimization techniques are used to calculate measurement uncertainties for materials accountability instruments in a fast breeder reactor spent-fuel reprocessing plant. Optimal measurement uncertainties are calculated so that performance goals for detecting materials loss are achieved while minimizing the total instrument development cost. The optimization methodology is useful in answering the following questions.

(1) Given limited development resources, what measurement technology improvements provide the maximum increase in accounting system performance?
(2) Which measurement uncertainties dominate the materials balance variance?
(3) What values of measurement uncertainties are required to meet a given performance goal?

Improved materials accounting in the chemical separations process (111 kg Pu/day) to meet 8-kg plutonium abrupt (1 day) and 40-kg plutonium protracted (6 months) loss-detection goals requires:

- process tank volume and concentration measurements having precisions $\leq$1%;
- accountability and plutonium sample tank volume measurements having precisions $\leq$0.3%, short-term correlated errors $\leq$0.04%, and long-term correlated errors $\leq$0.04%; and
- accountability and plutonium sample tank concentration measurements having precisions $\leq$0.4%, short-term correlated errors $\leq$0.1%, and long-term correlated errors $\leq$0.05%.

I. INTRODUCTION

Materials accounting systems for various facilities in the nuclear fuel cycle[1-5] traditionally calculate the materials accounting systems performance by proposing a measurement system based on current technology or reasonable extrapolations of current technology. The measurement uncertainties for each proposed instrument were combined and propagated to obtain an overall materials loss-detection sensitivity. In this paper the appro h is reversed. We select specific accounting performance goals and use optimization techniques to calculate measurement uncertainties required to meet these goals while minimizing the instrument's total development cost of the system.

The Hot Experimental Facility[6,7] (HEF) was chosen as the reference facility for the optimization calculations. It was designed under the Consolidated Fuel Reprocessing Program centered at Oak Ridge National Laboratory. The HEF incorporates a modified Purex process that allows coprocessing uranium and plutonium. The flow sheet is based on reprocessing 0.5 tonne/day of breeder reactor fuel. The major process areas are (1) spent fuel receiving and storage, (2) mechanical processing and feed preparation, (3) codecontamination/partitioning, (4) uranium purification, and (5) uranium-plutonium copurification. The HEF design includes a coconversion process that we do not address here.

II. MATERIALS ACCOUNTING PERFORMANCE GOALS

Table I lists fo r levels of materials accounting performance goals. The first two levels correspond to a likely range of measurement capabilities, the third and fourth levels to desired international and domestic goals. The first performance goal is based on state-of-the-art instrumentation. The second goal represents reasonable extrapolations of current technology. The third goal is based on International Atomic Energy Agency (IAEA) criteria and the fourth on Nuclear Regulatory Commission (NRC) goals that are now being considered.

Each performance goal includes detection of an abrupt (short-term) and a protracted (long-term) diversion with given detection and false-alarm probabilities. These quantities are used to calculate the maximum value of the materials balance standard deviation that will meet the performance goal.

Note that the plant throughput is ~111 kg of plutonium per day and that the chemical separation and feed preparation portions of the process can have an inventory of ~750 kg of plutonium.

TABLE I

PERFORMANCE GOALS

Goal	Amount @ Detection (kg Pu)	Detection Time	Detection Probability	False-Alarm Probability	Materials Balance Standard Deviation Upper Limit (kg Pu)
1. Current technology					
Abrupt	16	1 day	0.5	0.025	8
Protracted	150	6 months	0.5	0.025	75
2. Improved technology					
Abrupt	8	1 day	0.5	0.025	4
Protracted	40	6 months	0.5	0.025	20
3. IAEA					
Abrupt	8	7-10 days	0.95	0.05	2.4
Protracted	8	1 year	0.95	0.05	2.4
4. NRC					
Abrupt	2	1 day	0.5	0.025	1
Protracted	2	6 months	0.5	0.025	1

III. MATERIALS MEASUREMENT AND ACCOUNTING SYSTEM

The facility materials measurement and accounting system (MMAS) combines conventional materials accounting and near-real-time accounting (NRTA) and serves several functions including process monitoring, domestic safeguards, and international safeguards. It employs sampling and chemical analysis, weight and volume measurements, and nondestructive assay (NDA) instrumentation, supported by data base management and data analysis techniques. For conventional accounting the facility is divided into four MBAs:

(1) MBA 1 - fuel receiving, storage, chop, and leach;
(2) MBA 2 - chemical separations;
(3) MBA 3 - uranium-plutonium oxide storage; and
(4) MBA 4 - uranium-oxide storage.

In the process areas, conventional materials accounting is augmented by two NRTA strategies. In the first strategy, feed preparation processes were treated as one UPAA (UPAA 1) and chemical separations processes were treated as another (UPAA 2 3). In the second, the chemical separations UPAA was further subdivided into UPAA 2 (codecontamination/partitioning processes) and UPAA 3 (uranium-plutonium copurification processes).

Measurement points were identified in Ref. 8, as were applicable measurement types and errors representative of current technology. The reference measurements are used for process control[10] and materials accounting. This measurement system is a reasonable starting point for the optimization calculations. Having such a reference system puts into perspective the size of improvements to be made to meet proposed performance goals.

Table II lists measurement points, measurement types, and measurement errors used by the materials accounting system. Each measurement is specified by:

(a) a precision (ϵ) with variance σ_ϵ^2,
(b) a short-term correlated error component (η) with variance σ_η^2,
(c) a long-term correlated error component (δ) with variance σ_δ^2,
(d) a calibration frequency.

The short-term correlated error represents those errors that are correlated only over each calibration period. Long-term correlated errors persist over all accounting periods and include errors in the primary and secondary standards, any inherent bias in sampling, and measurement methods and sample-standard mismatch. All errors are assumed to be normally distributed with mean zero. A mixed measurement error model is used, $m = \mu(1 + \epsilon + \eta) + \delta$, where μ equals the actual value and m equals the measured value.

IV. MMAS PERFORMANCE

MMAS materials loss-detection levels using the base case measurement system (Table II) were calculated using the modeling, simulation, and analysis approach.[1-5] Table III presents loss-detection levels for each of the UPAAs. Results are given for 1 day (abrupt) and 6 months (protracted) for two pairs of detection and false-alarm probabilities that coincide with Table I performance goals. Two cases of recalibration frequency are given for each UPAA:

(1) no recalibration within the accounting period and
(2) recalibration of the feed and product concentration measuring instruments once every week.

TABLE II

KEY MEASUREMENT POINTS[a]

Measurement Point	Measurement Type[b]	Current Measurement Errors (5, 12): Precision	Short-Term Correlated	Long-Term Correlated
Spent-fuel receiving area	NDA	4	3	2
Disassembly/shear area	Est	20	-[c]	-
Voloxidizer	Est	20	-	-
Continuous dissolver	Est	20	-	-
Leached-hulls NDA unit	NDA	10	5	5
Batch dissolver	V	3	3	1
	C	1.5	1	1
Batch-dissolver hulls NDA unit	NDA	10	5	5
Batch dissolver surge tanks (2)	V	3	3	1
	C	1.5	1	1
Digester surge tanks (2)	V	3	3	1
	C	1.5	1	1
Primary centrifuge	NDA	10	5	5
Secondary dissolver	V	3	3	1
	C	7	3	3
Solids sample tank	NDA	10	5	5
Feed solution surge tank	V	3	3	1
	C	1.5	1	1
Accountability tank	V	0.3	0.1	0.1
	C	1	0.3	0.3
Feed adjustment tank	V	3	3	1
	C	1.5	1	1
HA feed tank	V	3	3	1
	C	1.5	1	1
HC column	Est	10	-	-
HCP reduction vessel	V	3	3	1
	C	1	0.5	0.2
1A feed tank	V	3	3	1
	C	1	0.5	0.2
1A column	Est	10	-	-
1APU stream	F	3	0.5	0.2
	C	1	0.5	0.2
2A feed tank	V	3	3	1
	C	1	0.5	0.2
2A column	Est	5	-	-
2B column	Est	5	-	-
3A feed tank	V	3	3	1
	C	1	0.5	0.2
3A column	Est	5	-	-
3B column	Est	5	-	-
Pu stripper feed tank	V	3	3	1
	C	1	0.5	0.2
Pu stripper	Est	10		
Pu concentrator	V	3	3	1
	C	1	0.5	0.2
Pu catch tank	V	3	3	1
	C	1	0.5	0.2
Pu sample tank	V	0.3	0.1	0.1
	C	0.3	0.3	0.1
HA centrifuge	Est	20	-	-
3A contactor	Est	20	-	-
RS column	Est	10	-	-

[a] Adapted from Ref. 6.

[b] Est = estimation, V = volume, C = concentration, and F = flow rate.

[c] Correlated errors for inventory measurements and estimates are not listed because these errors tend to cancel when beginning and ending inventories are approximately equal.

TABLE III

MATERIALS ACCOUNTING LOSS-DETECTION LEVELS USING CURRENT MEASUREMENT TECHNOLOGY

	kg (Pu)			
	DP = 0.5, FAP = 0.025[a]		DP = 0.95, FAP = 0.05	
	1 Day	6 Months	1 Day	6 Months
UPAA 1 - Feed Preparation				
No recalibration	23.2	1272	38.3	2099
Weekly recalibration	23.2	746	38.3	1230
UPAA 2 - Codecontamination/Partitioning				
No recalibration	11.8	578	19.5	954
Weekly recalibration	11.8	218	19.5	360
UPAA 3 - Copurification				
No recalibration	11.1	568	18.2	937
Weekly recalibration	11.1	228	18.2	376
UPAA 2 3 - Chemical Separations				
No recalibration	15.2	186	25.1	307
Weekly recalibration	15.2	144	25.1	238

[a] DP is detection probability and FAP is false-alarm probability.

Goal 1, abrupt and protracted loss-detection goals, can be met in the chemical separations area (UPAA 2 3). The protracted goal can be met only by weekly recalibration of feed and product concentration measuring instruments. Abrupt loss-detection goals can be met in the codecontamination/partitioning area (UPAA 2) and the copurification area (UPAA 3). The loss-detection sensitivity for UPAA 1 will not meet goal 1 performance. Goals 2, 3, and 4 cannot be met by current measurement technology in any of the UPAAs.

The physical inventory taking (PIT) loss-detection sensitivity is equivalent to that of the 6-months accounting period. Therefore, PIT will satisfy performance goal 1 only in the chemical separations area and only if the feed and product concentration measuring instruments are recalibrated once every week.

The problem now is to calculate measurement uncertainties that will meet each of the performance goals while minimizing the total system development cost.

V. OPTIMAL ALLOCATION OF MEASUREMENT UNCERTAINTIES

The problem of calculating minimum development cost uncertainties to meet a given systems performance goal can be formulated as an optimization problem. To do so, we must write a set of constraint equations for measurement error components (σ_i) and an objective function that relates them to instrument development cost. The materials balance standard deviation (σ_{MB}) must be less than or equal to a specified abrupt systems performance goal (σ_a) and a specified protracted systems performance goal (σ_p).

In addition to the constraints imposed by materials balance uncertainties, upper and lower limits on allowable standard deviation for each measurement error component σ_i are desirable to assure a reasonable uncertainty calculation. Clearly the upper limit (σ_{ui}) should correspond to the current instrument performance and the lower limit (σ_{li}) should be based on the judgment of instrument designers about reasonably attainable instrument uncertainties. Therefore, the constraints for our problem are given by

$$\left(\sum_{i=1}^{N_m} B_{ai}\sigma_i^2\right)^{1/2} = \sigma_{MB} \leq \sigma_a \quad ,$$

$$\left(\sum_{i=1}^{N_m} B_{pi}\sigma_i^2\right)^{1/2} = \sigma_{MB} \leq \sigma_p \quad , \qquad (1)$$

$$\sigma_{li} < \sigma_i \leq \sigma_{ui} \quad (i = 1, \ldots, N_m) \quad .$$

The coefficients B_{ai} and B_{pi} are calculated from the amount of material being measured and the length of the accounting period.

To complete formulating uncertainty allocation as an optimization problem, the cost of uncertainty reduction must be incorporated in an objective function. For this study we chose an equilateral hyperbola to represent the relative cost of improving a measurement uncertainty. Any other convex cost function can be used for each measurement uncertainty component. The relative cost (C_i) of improving the i^{th} measurement error component is given by

$$C_i = \frac{\sigma_{ui} - \sigma_{li}}{\sigma_i - \sigma_{li}} - 1 \quad , \qquad (2)$$

where $\sigma_{ui} \equiv$ upper limit of σ_i (representative of current technology), and $\sigma_{li} \equiv$ lower limit of σ_i (probable limit of development).

VI. RESULTS

We used optimization techniques to calculate measurement uncertainties so that performance goals for detecting materials loss are achieved while total development cost of the instruments is minimized. Measurement uncertainties were calculated for each UPAA and for several cases of instrument recalibration. For each UPAA, values for the measurement uncertainty components were restricted by specific ranges and by the materials balance standard deviation equations for abrupt and protracted losses. The cost of improving each measurement uncertainty component is determined by a hyperboli cost function. Therefore, where calculated measurement uncertainty is less than what is currently achievable, a development cost was imposed.

Table IV lists relative costs for developing the instrument systems that meet each performance goal. One cost unit is the relative cost of attaining a measurement uncertainty that is one-half that of current measurement technology $[\sigma_i = (1/2)\sigma_{ui}]$. Each halving of measurement uncertainty costs twice what the previous halving did plus 1. For example, the cost of achieving $\sigma_i = (1/4)\sigma_{ui}$ is 3 and of $\sigma_i = (1/8)\sigma_{ui}$ is 7. UPAA 2 3 with weekly recalibration of the plutonium concentration measuring instruments for the

TABLE IV

RELATIVE COST OF ACHIEVING THE PERFORMANCE GOALS

	Goal 1	Goal 2	Goal 3	Goal 4
UPAA 1				
No recalibration	20	111	1947	2546
Weekly recalibration	9	64	-	-
Daily recalibration	-	53	942	1350
UPAA 2 3				
No recalibration	0.8	32	727	1544
Weekly recalibration	0	22	-	-
Daily recalibration	-	19	495	738
UPAA 2				
No recalibration	11	74	1404	2023
Weekly recalibration	2	36	-	-
Daily recalibration	-	28	595	853
UPAA 3				
No recalibration	9	65	1263	1666
Weekly recalibration	1.7	29	-	-
Daily recalibration	-	21	518	735

accountability and product sample tanks will meet goal 1. Hence, the total development cost of the system is zero. If periodic recalibration of key transfer measurements is performed, the relative cost of the system can be reduced by 30% or more. The relative cost of achieving goals 3 or 4 is between 20 and 50 times more than the cost for achieving goal 2.

Tables V and VI list optimal measurement uncertainties for the dominant inventories and transfers in UPAA 1 and UPAA 2 3 that meet the four performance goals (Table I) while minimizing total systems development cost. They list the measurement error components for the UPAA (ϵ, η, and θ) and their calculated value, current technology value, uncertainty contribution to the abrupt and protracted goals, and relative cost.

In-process inventory uncertainties are entirely a function of precision (ϵ). There are two types of inventory determinations: those determined by a single measurement or estimate (such as for the shear) and those calculated from the product of two measured values (such as for the HA feed tank volume and concentration).

Transfer uncertainties are a function of precision and short-term (η) and long-term (θ) correlated instrument errors. There are two types of transfer determinations: those made by a single measurement (such as for the spent fuel) and those calculated from the product of two measurements (such as for the accountability tank volume and concentration).

In the tables, inventory uncertainties are given first, followed by transfer uncertainties. Results are given for cases where instruments are not recalibrated during the accounting period and for periodic recalibration of key transfer measurements (excluding volume measurements). Note that small differences in measurement uncertainties, and hence relative cost, are not significant, because these differences could result from numerical inaccuracies in the optimization computer program. The dominant inventory uncertainty terms for UPAA 1 result from in-process inventory estimates in the shear, voloxidizer, and continuous dissolver, and volume and concentration measurements in the digesters and the feed solution surge tank. The dominant transfers

TABLE V

UPAA 1 DOMINANT MEASUREMENT UNCERTAINTIES
(1σ RSD)

Description	Current (1C)	Goal 1 No Recalibration	Goal 1 Weekly Recalibration	Goal 2 No Recalibration	Goal 2 Weekly Recalibration	Goal 2 Daily Recalibration	Goal 3 No Recalibration	Goal 3 Daily Recalibration	Goal 4 No Recalibration	Goal 4 Daily Recalibration
INVENTORIES										
Shear (ε)	2.0-1	2.0-1	2.0-1	1.3-1	1.3-1	1.3-1	2.3-2	2.3-2	1.0-2	[illegible]
Voloxidizer (ε)	2.0-1	1.4-1	1.3-1	5.7-2	5.8-2	5.5-2	8.1-3	9.9-3	4.4-3	5.2-3
Continuous dissolver (ε)	2.0-1	1.7-1	1.7-1	7.2-2	7.1-2	7.1-2	1.1-3	1.2-2	4.0-3	6.5-3
Digesters (2)										
Volume (ε)	3.0-2	3.0-2	3.0-2	2.6-2	2.7-2	2.7-2	4.2-3	5.2-3	1.9-3	1.7-3
Concentration (ε)	1.5-2	1.5-2	1.5-2	1.5-2	1.5-2	1.5-2	3.5-3	4.0-3	2.1-3	2.2-3
Feed solution surge										
Volume (ε)	3.0-1	3.0-2	3.0-2	1.9-2	1.9-2	1.9-2	2.8-3	3.5-3	1.3-3	1.8-3
Concentration (ε)	1.5-2	1.5-2	1.5-2	1.3-2	1.3-2	1.3-2	2.2-3	2.7-3	1.2-3	[illegible]
TRANSFERS										
Spent fuel (ε)	4.0-2	3.3-2	3.7-2	8.0-3	9.8-3	1.0-2	6.1-4	7.8-4	3.9-4	4.9-4
(η)	3.0-2	2.8-3	1.0-2	6.9-4	2.3-3	4.7-3	4.1-5	3.5-4	3.3-5	2.1-4
(θ)	2.0-2	1.5-3	3.1-3	6.0-4	7.1-4	7.6-4	3.6-5	4.6-5	2.8-5	[illegible]
Accountability tank										
Volume (ε)	3.0-3	[illegible]	3.0-3	1.8-3	2.1-3	2.2-3	1.4-4	1.8-4	9.2-5	1.2-4
(η)	1.0-3	7.2-4	9.9-4	2.3-4	2.8-4	2.9-4	1.4-5	1.8-5	4.2-5	1.5-5
(θ)	1.0-3	9.2-4	9.9-4	2.3-4	2.8-4	2.9-4	1.6-5	1.8-5	1.3-5	1.4-5
Concentration (ε)	1.0-2	9.6-3	9.9-3	2.6-3	3.1-3	3.3-3	2.0-4	2.0-4	1.6-4	1.7-4
(η)	3.0-3	1.4-3	3.0-3	3.3-6	3.1-3	2.2-3	2.0-5	1.7-4	1.7-5	1.1-4
(θ)	3.0-3	1.4-3	1.6-3	3.3-4	4.0-4	4.3-4	2.0-5	2.5-5	1.5-5	2.0-5

TABLE VI

UPAA 2.3 DOMINANT MEASUREMENT UNCERTAINTIES
(1σ RSD)

No.	Description	Current (1C)	Goal 1 No Recalibration	Goal 1 Weekly Recalibration	Goal 2 No Recalibration	Goal 2 Weekly Recalibration	Goal 2 Daily Recalibration	Goal 3 No Recalibration	Goal 3 Daily Recalibration	Goal 4 No Recalibration	Goal 4 Daily Recalibration
	INVENTORIES										
	HA feed tank										
3	Volume (ε)	3.0-2	3.0-2	3.0-2	1.3-2	1.3-2	1.3-2	1.9-3	2.2-3	[illegible]	[illegible]
4	Concentration (ε)	1.5-2	1.5-2	1.5-2	1.1-2	1.1-2	1.0-2	1.8-3	2.1-3	1.5-3	[illegible]
	2A feed tank										
12	Volume (ε)	3.0-2	3.0-2	3.0-2	1.3-2	1.3-2	1.3-2	2.1-3	2.6-3	1.7-3	[illegible]
13	Concentration (ε)	4.0-2	1.0-2	1.0-2	8.0-3	8.3-3	8.8-3	1.6-3	1.7-3	1.1-3	[illegible]
	TRANSFERS										
	Accountability tank										
29	Volume (ε)	3.0-3	3.0-3	3.0-3	2.6-3	1.7-3	2.7-3	1.8-4	2.1-4	1.6-4	[illegible]
30	(η)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.7-4	3.9-5	2.2-5	1.6-5	[illegible]
31	(θ)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.8-4	3.9-5	2.2-5	1.3-5	[illegible]
32	Concentration (ε)	1.0-2	9.6-3	1.0-2	3.7-3	4.3-3	4.3-3	3.8-4	3.1-4	1.7-4	1.9-4
33	(η)	3.0-3	2.6-3	3.0-3	[illegible]	1.5-3	2.9-3	2.8-5	2.1-4	9.8-6	[illegible]
34	(θ)	3.0-3	2.3-3	3.0-3	[illegible]	5.2-4	5.6-4	2.7-5	3.1-5	9.7-6	[illegible]
	Pu sample tank										
35	Volume (ε)	3.0-3	3.0-3	3.0-3	2.9-3	2.8-3	3.0-3	2.3-4	2.6-4	1.8-4	[illegible]
36	(η)	1.0-3	9.9-4	1.0-3	3.3-4	3.6-4	3.7-4	1.9-5	2.2-5	1.5-5	[illegible]
37	(θ)	1.0-3	9.8-4	1.0-3	3.3-4	3.6-4	3.8-4	1.9-5	2.2-5	1.0-5	[illegible]
38	Concentration (ε)	3.0-3	3.0-3	3.0-3	2.9-3	2.7-3	3.0-3	2.3-4	2.6-4	6.7-5	1.6-4
39	(η)	2.0-3	1.9-3	2.0-3	6.0-4	1.3-3	2.0-3	2.3-5	1.8-4	9.7-6	[illegible]
40	(θ)	2.0-3	1.8-3	2.0-3	6.1-4	6.0-4	6.7-4	2.5-5	2.7-5	9.7-6	[illegible]

are spent-fuel feed and accountability tank product. Of the two, spent-fuel NDA dominates transfer uncertainties and therefore requires greater development.

As shown in Sec. IV, goal 1 cannot be achieved in UPAA 1 with current measurement technology. With current measurements, σ_{MB} for 1 day is 11.6 kg of plutonium (10). For a 6-month balance σ_{MB} is 636 kg of plutonium (10) for no recalibration, and for weekly recalibration σ_{MB} is 373 kg of plutonium (10).

UPAA 1 optimal measurement uncertainties for dominant inventory and transfer terms that satisfy the four performance goals are summarized in Table V. To achieve goal 1 with weekly recalibration, errors in the estimates of the in-process inventory in the voloxidizer and continuous dissolver must be decreased from 20% each to 13% and 17%, respectively. The spent-fuel NDA η and θ measurement uncertainties must be reduced from 3% and 2% to 1% and 0.3%, respectively, and minor reductions are necessary in a few other measurement uncertainty components.

Goal 2 attainment requires modest improvements in inventory estimate errors and large improvements in transfer measurement errors.

Errors in the inventory estimates of the shear, voloxidizer, and continuous dissolver must be reduced from 20% to 13%, 6%, and 7%, respectively. We need spent-fuel transfer measurements having a precision $\leq 1\%$ and correlated errors of $\leq 0.2\%$ short-term and $\leq 0.07\%$ long-term. For the accountability tank, we need volume measurements having a precison $\leq 0.02\%$, a short-term correlated error $\leq 0.03\%$, and a long-term correlated error $\leq 0.03\%$; and we require concentration measurements having a precision $\leq 0.3\%$, a short-term correlated error $\leq 0.1\%$, and a long-term correlated error $\leq 0.04\%$.

To achieve goals 3 or 4 requires measurement improvements of approximately an order of magnitude for the inventories and two to three orders of magnitude for the key transfers. For example, these goals need inventory estimates that are <1% and transfer correlated errors that are <0.002%. Clearly, these goals will not be achieved without major breakthroughs in measurement technology and standards preparation.

Table VI lists measurement uncertainties and the relative cost of the dominant inventory and transfer measurements, the four performance goals, and the recalibration cases. For each goal, two cases were simulated:

(1) no recalibration during the accounting period, and
(2) periodic recalibration of the accountability tank and plutonium sample tank concentration measuring instruments, and the NDA instrument measuring the sludge.

We simulated weekly recalibrations for goal 1, both weekly and daily recalibrations for goal 2, and daily recalibrations for goals 3 and 4.

The dominant inventory uncertainties result from volume and concentration measurements of the HA feed tank and the 2A feed tank contents. For goal 1 with no recalibration, these two inventories have a combined standard deviation of 7.2 kg of plutonium, whereas the 1-day σ_{MB} is 8 kg of plutonium, with volume measurement making the larger contribution of the two components.

The dominant transfers are the accountability and plutonium sample tanks where volume and concentration measurements are made. Of the two measurement types, the concentration measuring instruments require more development.

Goal 1 can be achieved by current measurement technology if the transfer concentration measuring instruments are recalibrated weekly. To achieve goal 2 requires that $\sim 1\%$ volume and concentration measurements be made in process tanks; $\sim 0.3\%$ precision, $\sim 0.04\%$ calibration, and $\sim 0.04\%$ standards for volume measurements be made in primary transfer tanks; and $\sim 0.3\%$ precision, $\sim 0.2\%$ calibration, and $\sim 0.05\%$ standards for concentration measurements be made on samples from primary transfer tanks. To achieve goals 3 and 4 requires that measurement uncertainties be decreased by more than an order of magnitude.

Periodic recalibration of key instruments has a striking effect. For goal 2, as an example, compare the weekly, daily, and no recalibration cases for the η concentration error components of the accountability tank. Compared to the no recalibration case, weekly and daily recalibrations permit increasing η by a factor of ~ 3 and ~ 6, respectively. Also note that the relative cost of achieving goal 2 is decreased by $\sim 30\%$ for weekly recalibration.

VI. DISCUSSION

This paper demonstrates the use of optimization techniques to calculate measurement uncertainties that meet given materials accounting systems performance goals while minimizing the total instrument development cost. In this way we can answer the following questions.

(1) Given limited development resources, what measurement technology improvements provide the maximum increase in accounting system performance?
(2) Which measurement uncertainties dominate the materials balance variance?
(3) What values of measurement uncertainties are required to meet a given performance goal?

Proposed international and domestic safeguards goals require inventory measurement or estimate errors <0.3%, and transfer correlated errors <0.002%. In comparison, today's primary standards have errors of $\sim 0.04\%$. Clearly, these goals cannot be achieved without major breakthroughs in the measurement technology and standards preparation.

Achieving performance at the second level (8 kg of plutonium abrupt and 40 kg of plutonium protracted) may be a reasonable goal for the chemical separations area of the HEF. This requires improving in-process inventory measurement uncertainty to $\sim 1\%$ precision for process tank volume and concentration measurements. It also requires improving accountability and plutonium sample tank transfer measurement uncertainties to $\sim 0.04\%$ volume calibration, $\sim 0.04\%$ volume standards, $\sim 0.1\%$ concentration calibration, and $\sim 0.05\%$ concentration standards.

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